Can measures of limb loading and dynamic stability during the squat maneuver provide an index of early functional recovery following unilateral Total Hip Arthroplasty?

Abstract:

Objective: To investigate limb loading and dynamic stability during squatting in the early functional recovery of total hip arthroplasty (THA) patients.

Design: Cohort study

Setting: Inpatient rehabilitation clinic.

Participants: A random sample of 61 THA patients (34♂/27♀; 62±9 yrs, 77±14 kg, 174±9 cm) was assessed twice, 13.2±3.8 days (PRE) and 26.6±3.3 days post-surgery (POST), and compared with a healthy reference group (REF) (22♂/16♀; 47±12yrs; 78±20kg; 175±10cm).

Interventions: THA patients received two weeks of standard in-patient rehabilitation.

Main Outcome Measure(s): Inter-limb vertical force distribution and dynamic stability during the squat maneuver, as defined by the root mean square (RMS) of the center of pressure in antero-posterior and medio-lateral directions, of operated (OP) and non-operated (NON) limbs. Self-reported function was assessed via FFb-H-OA 2.0 questionnaire.

Results: At PRE, unloading of the OP limb was 15.8% greater ($P<.001$, $d=1.070$) and antero-posterior and medio-lateral center of pressure RMS were 30-34% higher in THA than REF ($P<.05$). Unloading was reduced by 12.8% towards a more equal distribution from PRE to POST ($P<.001$, $d=0.874$). Although medio-lateral stability improved between PRE and POST (OP: 14.8%, $P=.024$, $d=0.397$; NON: 13.1%, $P=.015$, $d=0.321$), antero-posterior stability was not significantly different. Self-reported physical function improved by 15.8% ($P<.001$, $d=0.965$).

Conclusion(s): THA patients unload the OP limb and are dynamically more unstable during squatting in the early rehabilitation phase following total hip replacement than healthy adults. Although loading symmetry and medio-lateral stability improved to the level of healthy adults with rehabilitation, antero-posterior stability remained impaired. Measures of dynamic stability and load symmetry during squatting provide quantitative information that can be used to clinically monitor early functional recovery from THA.

Key words: rehabilitation; arthroplasty; osteoarthritis; total hip replacement

Abbreviations

THA	Total hip arthroplasty
TKA	Total knee arthroplasty
REF	Reference group
OP	Operated leg
NON	Non-operated leg
CoP	Center of pressure
RMS	Root mean square

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Squatting is a fundamental movement that is frequently performed during tasks of everyday living including sitting down, standing up, lifting objects, and climbing stairs.[1,2] Compared with other common activities such as standing and walking, successful execution of the squatting maneuver places greater demands on hip and knee musculature and remains a common goal in many orthopedic rehabilitation programs, particularly those involving osteoarthritis of the hip and knee and its surgical intervention.[3–8]

With the advent of affordable force-measurement systems, quantification of limb loading during the squat maneuver has recently been used as a clinical outcome measure to monitor the progression of rehabilitation in unilateral knee osteoarthritis and following total knee arthroplasty (TKA).[2,3,5–7] These studies have typically observed asymmetrical loading between affected and non-affected limbs or slow and unbalanced movement execution during squatting. These deficits remain even after the osteoarthritic joint has been replaced and have been observed in some studies up to 16 months after the arthroplasty.[3,4]

Despite the attention squatting quality has received in patients with knee osteoarthritis and, to a smaller extent TKA, little is known about the squatting quality in patients with osteoarthritis of the hip and following total hip arthroplasty (THA). The few studies that have analyzed squat maneuver in THA patients have also reported asymmetrical limb loading but have focused mainly on patients with movement problems and more than a year post-surgery.[4,8] To the best of our knowledge, quantification of the squat maneuver during early functional recovery of patients following unilateral THA has not been evaluated. As highlighted by Talis et al.,[8] quantification of the squat maneuver during early recovery may be critical for development of effective training and rehabilitation interventions.

The aim of this study was to explore the use of limb loading and dynamic stability during the squat maneuver to monitor the clinical progression and early functional recovery of patients following unilateral THA. We expected that at the onset of inpatient rehabilitation, THA patients would show distinct unloading of the operated limb and instability during execution of the squat. Further, we expected only small to medium improvements in these deficits following two weeks of inpatient rehabilitation, since persistent unloading of the operated limb during squatting has been reported 19 months postoperatively in THA patients.[4,8]

METHODS

Participants

Sixty-nine patients who had undergone total hip replacement surgery between April and June 2011, were recruited to participate in this study. All patients attended a single rehabilitation clinic (Medical Park St. Hubertus, Bad Wiessee, Germany) one week following their release from hospital. Participants were randomly sampled from all (~300) hip arthroplasty patients attending the clinic over the period of the investigation. Prior to the first measurement, inclusion criteria were verified in an interview. All participants were initially screened for the following inclusion criteria: (1) patients needed to have a primary arthroplasty, not a revision, (2) be free of other pathologies affecting the lower extremities or the back, and (3) be able to stand and perform the requested squat maneuver pain free and without aides. Three patients did not meet the inclusion criteria (one revision, one drop foot, one pain) and were excluded from the study. An additional five patients were excluded because of illness (two with gastrointestinal virus) or experienced injuries unrelated to the study protocol (one accident, two muscle strains) in the period between measurements. The mean (±SD) age, weight and height of the remaining sixty-one patients (34 males, 27 females) was 61.8 ± 9.2 years, 76.9 ± 13.6 kg, and 174 ± 9 cm, respectively. The ability of the patients to undertake a squatting maneuver was quantified twice during their in-patient rehabilitation; (PRE) within the first week of arriving at the rehabilitation clinic (13.2±3.8 days post-operatively), and (POST) at discharge from the clinic two weeks later (26.6±3.3 post-operatively). Between PRE and POST measurements, THA patients received a standard daily in-patient physical therapy treatment involving progressive resistance training, graduated balance and agility exercises, and manual therapy. Over the two week rehabilitation period, patients received between 51 and 59 treatment units, equating to approximately 136 to 187min of net therapy time per day.

A reference group (REF) consisting of 38 healthy adults (22males, 16 females, age: 47.4±11.9 yrs, weight: 77.8±19.9 kg, height: 175±10 cm) was recruited from clinical staff and patients during the same period. All participants in the reference group were free of injuries of the lower back and extremities and provided informed written consent prior to participation. All study procedures complied with the principles of the Declaration of Helsinki for ethical research in humans [9] and were approved by the local ethics committee.

Protocol

Prior to undertaking the squatting maneuver, THA patients completed the *Function Assessment Questionnaire Hannover for Osteoarthritis* (FFb-OA-H 2.0)[10], a German specific tool for evaluating functionality in THA and TKA patients that has been shown to be sensitive to changes in function over time[10], to quantify their perceived functional status. The self-reported questionnaire contains 18 questions regarding the execution everyday tasks and is answered on a scale of zero to two (2-“yes, I can perform the task without difficulty”, 1-“yes, but only with difficulty”, 0-“no, only with aids or helping person”). A total perceived functionality score was calculated by dividing the sum of all answered items by the maximum possible score.[10] A functionality score of 100% represents full function with no limitations, while a score of 0% indicates that all movement tasks in question can only be performed with assistance.

Participants were asked to stand with each foot on one of two pedar® posturo pressure mats (novel GmbH[a]). Each mat had a sensing surface of 44 cm x 20 cm, and incorporated 220 capacitance-based, individually calibrated pressure sensors. The root mean square error for static and dynamic pressure derived from these capacitance-based sensors is reported less than < 0.5%, with the precision and accuracy of the centre of pressure (CoP) displacement typically <.04 cm and <0.2 cm, respectively[11]. The two mats were positioned 10, 15, or 20 cm apart depending on individual patient comfort. Once established, the relative position of the mats was maintained for the post-measurement. A therapeutic chair was positioned directly behind participants. The adjustable seating surface of the chair was tilted (30° declination) and the height was individually fixed to ensure that participants approached but did not exceed 90 degrees hip flexion at the lowest squat position. Participants were instructed to keep their arms outstretched and positioned horizontally in front of their body. Two fingers of each hand were placed on a low friction linear bearing attached to a training pole. The parallel arrangement of the training poles ensured each participant maintained their trunk in an upright, slightly forward leaning position during the squat maneuver.

Squat execution commenced from an erect upright position (Fig. 1, left) and participants were instructed to perform two sets of five consecutive squats at their preferred movement velocity. The lowest position of each squat was reached when subjects first perceived the chair (Fig. 1, right), at which time they were instructed to immediately start the upward return movement of the squat. A one minute rest period was provided between each exercise set.

Pressure data for each limb were recorded at 45Hz during the squat and a synchronized video signal was simultaneously recorded with a standard digital-8 camera (Sony, DCR-TRV340E). The video signal was used to manually divide the data into single squat segments. Pressure data and the coordinates for CoP beneath each foot were subsequently exported from the proprietary software. Data were further post-processed using Matlab software [b] and only six squats were selected by ignoring the first and last squat from each set. Force distribution and CoP stability parameters were calculated for each single squat and average values for the six squats calculated.

Inter-limb load distribution

Vertical ground reaction force was retrieved for each foot separately by dividing the average pressure calculated beneath the foot by the total area of the active sensors. Force differences between limbs were calculated for each time frame and averaged over the duration of the squat. In the reference group, the value of the right limb was arbitrarily subtracted from the left limb. The extent of loading symmetry between limbs was estimated using the symmetry index (Fz_{ratio}) described elsewhere and outlined below:[3]

$$Fz_{ratio} = \frac{operated\ /\ left\ limb}{non\text{-}operated\ /\ right\ limb} \quad (1)$$

Given that previous research has shown limb dominance has no effect on distribution weight between limbs and movement of the center of mass during the sit-to-stand maneuver[12], inter-limb load difference in the reference group was calculated by subtracting right from left limb values, while the force ratio was calculated by dividing values for the left by those of the right. Although we believe this may in part reflect difficulties associated with the definition and measurement of limb dominance[13,14], we adopted the widely accepted method described in the review of Sadeghi et al.[14] in which values for the left limb are expressed relative to the right.

As an estimate of between-trial reliability, mean and standard deviations of inter-trial differences were calculated analyzing the two trials recorded on the same day for the THA group at each measurement instance and the reference group separately.[15] Each trial consisted of three consecutive squats. We observed no systematic off-sets between trials (e.g. learning effects) with the mean differences between trials being as low as 1.6-6.5 N. Reliability was considered low with standard deviations of the differences ranging between 20-24 N.

Center of pressure stability

The displacement of the CoP beneath each foot was analyzed separately. Root-mean-square (RMS) values in both the medio-lateral and antero-posterior direction were calculated as measures of dynamic stability.[16,17]

Statistics

The R statistics programming language [c] was used for all statistical procedures. The Kolmogorov-Smirnov test was used to test for normal distribution. Outcome variables were normally distributed, so means and standard deviations have been used as summary statistics. Parametric data were analyzed statistically with paired (pre vs. post) and unpaired (patients vs. reference) Student t-tests with Welch adaptations where appropriate. An alpha level of 5% was set *a priori*. *Cohen's d* was calculated as an effect size estimate. Differences in the non-parametric questionnaire items were analyzed for significance using the exact Wilcoxon Signed Rank Test. Spearmen correlation coefficients were used to investigate potential associations between changes in self-reported functionality score and objective measures of limb loading and dynamic stability.

RESULTS

Perceived functionality

Mean functionality scores improved (15.8%) significantly from 49.2% at PRE to 65.0% at POST ($CI_{95\%}$=11.5-19.9%, P<.001, d=0.965, Fig. 2). Of the 61 patients, 49 patients rated their total function as improved over the rehabilitation period, nine rated their function as worse, and three as unchanged. Fifteen of the 18 questionnaire items (83%) were rated as significantly improved between PRE and POST. Three items showed no statistical change over the two week period. However, these items specifically address lifting tasks that the majority of patients were not allowed to execute during the study, and so most patients left these unanswered. The change in functionality score did not correlate significantly with change in any of the limb loading or dynamic stability parameters, with all correlation coefficients below 0.30.

Inter-limb load distribution

THA patients demonstrated an unloading of the operated limb at the PRE measurement. The ratio of forces beneath the operated and non-operated limb (0.84±0.14) was 15.8% lower than the reference group (0.97±0.09, P<.001, d=1.070). This asymmetry in loading was significantly reduced (12.8%) with two weeks of rehabilitation (P<.001, d=0.874, Fig. 3) and the force ratio between limbs in the THA group was not significantly different from the reference group at the POST measurement (P=.290).

Center of pressure

At PRE measurement, THA patients had 30-34% higher antero-posterior and medio-lateral stability values in both the operated and non-operated limbs compared with REF (Fig. 4).

At POST measurement, medio-lateral stability was significantly reduced in the operated limb by 14.8% (P=.024, d=0.397, Fig. 4c) and in the non-operated limb by 13.1% (P=.015, d=0.321, Fig. 4d). Although medio-lateral stability in the operated limb (0.115±0.074 m/s) was not significantly different to REF (0.104±0.055 m/s) at POST (P=.385), medio-lateral stability of the non-operated limb remained significantly higher (19.2%) at POST when compared with REF (P=.049, d=0.371)

Anterio-poster instability was not significantly reduced from PRE to POST (operated: P=.096; non-operated: P=.386) and hence remained significantly higher in THA patients compared with REF (operated: P=.008, d=0.515, Fig. 4a; non-operated: P=.001, d=0.712, Fig. 4b).

DISCUSSION

THA patients in this study showed a marked asymmetry in lower limb loading within two weeks of surgery, with the operated limb having 16% lower force, on average, than that of the non-operated limb during squatting. The reasons for these observed impairments may be manifold including muscle strength deficits, pain response, and subconscious motor-adaptations.[18,19] Comparing these results to previous studies, the observed unloading of the operated THA limb is consistent with loading patterns observed following TKA,[3,7] but is somewhat higher than the 10% unloading previously observed by Turcot et al.[2] in females with advanced (end-stage) hip osteoarthritis. This level of loading asymmetry is likely too low to explain the concomitant impairment in dynamic stability alone.[20,21] Although further research is required, factors such as apprehension, residual pain and deficits in muscle strength might, therefore, result in a reluctance to load the operated leg within one week of surgery. Interestingly, unloading of the operated limb in the current study was considerably lower one week after THA surgery (Fz_{ratio}=0.84) than that reported previously in THA some 12-19 months post-surgery (Fz_{ratio}=0.64).[8] Although comparisons between studies are hampered by differences between clinical groups, it is possible that the large loading asymmetry observed by Tallis et al.[8], compared with the relatively higher levels of symmetry observed in our and Turcot's study[2], reflect a natural deterioration in loading symmetry between operated and non-operated limbs in THA patients. However, further longitudinal cohort studies, specifically evaluating the transition from in-patient rehabilitation to everyday life, are required to ascertain whether the relatively symmetrical loading observed in THA patients' following surgery is maintained over the longer period, once patients return to home care.

How did load characteristics progress after two weeks of inpatient rehabilitation? While previous research has reported unloading of the operated limb for up to several years after THA surgery[4,8], we were able to demonstrate that THA patients improved their side-to-side symmetry markedly with as little as two weeks of rehabilitation. This improvement was evident by a return toward a balanced force distribution between limbs similar to that of the healthy reference group. Interestingly, Drabsch et al.[4] also observed that even 12 months post-operatively, loading symmetry ratios as low as 0.4 could be dramatically improved to 0.77 through as little one week of intensive training. While the present experimental setup did not allow for a mechanistic explanation for the change in weight-distribution in our cohort, the rapid progress observed in our study and in the study of Drabsch et al.[4] suggest that the improvement may not be due to strength improvements, considering the response time of muscular adaptions. Therefore, we believe that the rapid improvements in loading symmetry may be attributed to other factors, including reduced pain or a more conscious and concentrated movement execution which is stressed during rehabilitation. Interestingly, although self-reported functionality scores and weight distribution both improved over time, we found no significant correlation among these measures. Thus, everyday functionality assessed in the questionnaire is independent of symmetrical and stable squatting execution. Symmetrical movement execution, however, is considered clinically important since asymmetry leads to overloading of the non-operated limb and early-onset osteoarthritis and degeneration.[22,23] Objective measures of symmetry during the squatting maneuver, therefore, would appear more sensitive to functional abnormalities than self-reported measures, and their implementation in monitoring therapeutic interventions may help to promote symmetrical limb loading and prevent early-onset osteoarthritis in the non-operated limb.

Besides the initial unloading of the operated limb, we also demonstrated that THA patients had reduced medio-lateral and antero-posterior stability during the squat maneuver when compared with the healthy reference group. To the best of our knowledge these dynamic instabilities have not previously been identified in THA patients and are likely to be of clinical importance given that reduced stability of CoP parameters have been linked with falls risk in the elderly.[24,25] Interestingly, medio-lateral stability in this study was reduced significantly in both limbs following two weeks of in-patient therapy, and approached that of the healthy reference group in the operated limb. Although we hypothesized small improvements in dynamic stability, we were surprised by the extent of improvement observed in medio-lateral stability in our THA patients (*Cohen's d* 0.3-0.4).

In contrast to the change in medio-lateral stability, antero-posterior stability did not improve over the two-week rehabilitation intervention, leaving the THA patients still deficient at the time of their clinic release. We suggest two possible explanations as to why antero-posterior stability was not improved with rehabilitation. First, to control antero-posterior CoP movement, patients need to flex the hip joint and this is painful for those with end-stage hip osteoarthritis. Thus, the reduced antero-posterior stability may reflect a learned avoidance strategy or habitual movement pattern adopted prior to surgery.[19] Regaining trust in the new joint and relearning proper squatting execution is a time consuming process and we believe that it should be initiated as early as possible during rehabilitation. Second, previous research has shown that THA patients may have reduced strength of the surrounding hip musculature, particularly of the hip extensors.[8,26] Considering that squatting places great demands on the hip extensors,[27] THA patients may not be able to stabilize the hip joint within the dynamics of the squatting downward movement. In either case, our findings indicate that THA patients in this study were not fully recovered at the end of their inpatient rehabilitation, despite demonstrating symmetrical limb loading during squatting. Although previous studies have advocated that symmetry of limb loading be used to guide post-surgical rehabilitation in this cohort, we believe that additional information can be gained by including measures of dynamic stability. Although further research is required, we recommend that therapists consider measures of dynamic movement stability, with emphasis on antero-posterior stability when evaluating the clinical progression of THA patients.

Study Limitations

This study has a number of limitations that should be considered when interpreting the results. First, we characterized the early functional recovery of THA patients only during two weeks of in-patient rehabilitation following surgery. We recognize that deficits in strength and performance in functional activities have been observed even after 12 month post-surgery and we were not expecting our patients to fully recover within this time period.(4,8,26) Nonetheless, we know from previous research(28,29) that function is improved dramatically within the first few weeks of surgery. Moreover, we were able to objectively quantify recovery at this early stage of post-surgical rehabilitation. A second potential limitation of our study is that we did not individually age-match the reference and patient groups. Elderly adults often present with significant comorbidities and orthopedic pathologies of the lower extremity and have been shown to have impaired movement symmetry.(30) As such, we specifically chose to analyze a younger reference group to ensure near-optimal squatting execution, which remains the therapeutic goal of our post-surgical rehabilitation center.(31)

Moreover, previous research by Zijlstra et al.[32] has shown that movement times, vertical power and acceleration of the centre of mass during the sit to stand movement are not significantly different between healthy young adults (21 to 44 years) and elderly adults without health comorbidities (70 to 79 years). Third, although force platforms are more commonly used to evaluate CoP trajectory, this study used a portable pressure array to monitor movement of the CoP during the squat maneuver. Although the performance characteristics and spatial resolution of pressure platforms are known to influence the accuracy of force and COP measurements, the capacitive, elastomer-based pressure sensors used in this study have been shown to yield CoP and force comparable to conventional force plates.[11] Moreover, based on the findings of the current study, measures derived from capacitive-based pressure arrays are sufficiently sensitive to detect early post-surgical recovery in weight distribution and dynamic stability in THA patients.

CONCLUSION

In summary, this study demonstrates that early THA patients perform squats with an unloading of the operated limb and reduced dynamic stability. Although limb loading became more symmetric and medio-lateral stability improved to levels observed in a healthy reference group, antero-posterior stability remained unchanged with two weeks of inpatient rehabilitation. Given that reduced dynamic stability has been linked with falls risk in the elderly, we believe that measures of limb loading and dynamic stability during the squat maneuver provide important insights into early functional recovery of patients following unilateral THA.

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FIGURE CAPTIONS

Figure 1. Experimental set-up showing pressure mats, and therapeutic chair with tilted seat surface. Participant at starting position in erect stance (left) and at lowest point (right), touching the chair’s surface before moving up again. Participants were instructed to keep their arms out stretched in front of their body with two fingers of each hand were placed on a low friction linear bearing attached to a training pole. The parallel arrangement of the training poles ensured each participant maintained their trunk in an upright, slightly forward leaning position.

Figure 2. Density plot of total perceived functionality score assessed with *Function Assessment Questionnaire Hannover for Osteorathritis* (FFb-OA-H 2.0). Functionality score range from 0% (no functionality) to 100% (full functionality). Perceived functional ability improved by 15.7% (CI=11.5-19.9%) from pre (light) to post (dark) and following two weeks of regular in-patient rehabilitation ($P<.001$, $d=0.965$).

Figure 3. Ratio of inter-limb force distribution for THA patients (operated divided by non-operated) at pre and post measurement compared to ratios (left divided by right) of a healthy reference group. Presented are box plots, individual values, Student t-tests p-values and Cohen’s d as an estimate of effect size.

Figure 4. Antero-posterior (top) and medial-lateral sway (bottom) of operated (left column)

and non-operated (right column) limbs compared to those of a reference group.